THE MINDFUL UNIVERSE Part II

QUANTUM APPROACHES TO CONSCIOUSNESS.

1. Introduction.

Quantum approaches to consciousness are sometimes said to be motivated simply by the idea that quantum theory is a mystery and consciousness is a mystery, so perhaps the two are related. That opinion betrays a profound misunderstanding of the Nature of quantum mechanics, which consists fundamentally of a pragmatic scientific solution to the problem of the relationship between mind and matter.

The key achievement of the founders of quantum theory was to forge a rationally coherent and practically useful linkage between the two kinds of descriptions that jointly comprise the foundation of science. Descriptions of the first kind are accounts of psychologically experienced empirical findings, expressed in a language that allows us to communicate to our colleagues what we have done and what we have learned. Descriptions of the second kind are specifications of physical features, expressed by assigning mathematical properties space-time points. Bohr, Heisenberg, Pauli, and their colleagues, created a new way of linking these two kinds of descriptions, and this idea was extended by John von Neumann from the domain of atomic science to the realm of neuroscience and the problem of the relationship between the minds and brains of human beings.

This new approach to the relationship between the psychologically and physically described components of scientific practice was achieved by abandoning the classical conception of the physical world that had ruled science since the time of Newton, Galileo, and Descartes. The building blocks of science were shifted from descriptions of the behaviors of tiny bits of mindless matter to accounts of *the actions that we take to acquire knowledge* and of the *knowledge that we thereby acquire*. Science was transformed from its seventeenth century form, which effectively excluded our conscious thoughts from any fundamental role in the mechanical workings of Nature, to its twentieth century form, which focuses on our active engagement with Nature, and what we can learn by taking appropriate action.

Twentieth century developments have thus highlighted the fact that *science is a human activity* that involves us not as passive witnesses of a mechanically controlled universe, but as agents that can choose to perform causally efficacious actions. The basic laws of Nature, as they are now understood, not only fail to determine how we will act, but moreover inject our *choices about how to act* directly into the dynamical equations. Human choices, which are both empirically accessible and consciously controllable, become the key input parameters, replacing classically conceived microscopic variable, which are *empirically inaccessible* and in principle uncontrollable.

This new understanding underlies the following pronouncements of Werner Heisenberg and Niels Bohr:

"The conception of the objective reality of the elementary particles has thus evaporated not into the cloud of some obscure new reality concept, but into the transparent clarity of a mathematics that represents no longer the behavior of the particle but rather our knowledge of this behavior." (Heisenberg, 1958)

"In the great drama of existence we ourselves are both actors and spectators." (Bohr, 1963: 15, 1958: 81)

Wheeler calls the observers "participants" to emphasize the essentially *active role of conscious agents* in quantum dynamics.

Comprehending this new conception of the relationship between the psychologically experienced empirical side and the mathematically described physical side of the scientific endeavor requires an appreciation of a certain novelties in the logical structure of quantum theory. This conceptual re-organization can be understood without becoming enmeshed in technical mathematical details.

The Classical-Physics Approach.

To grasp the essential change one must know what came before.

Classical physics arose from the theoretical effort of Isaac Newton to account for the findings of Johannes Kepler and Galileo Galilei. Kepler discovered that the planets move in orbits that depend on the location of other physical objects - such as the sun - but not on the manner or the timings of our observations: minute-by-minute viewings have no more influence on a planetary orbit than daily, monthly, or annual observations. The nature and timings of our observational acts have no effect at all on the orbital motions described by Kepler. Galileo observed that certain falling terrestrial objects have similar properties. Newton then discovered that he could explain *simultaneously* the celestial findings of Kepler and the terrestrial findings of Galileo by postulating, in effect, that all objects in our solar system are composed of tiny planet-like particles whose motions are controlled by *laws* that refer to the relative locations of the various particles, and make no reference to any conscious acts of experiencing. These acts are taken to be simply passive witnessings of macroscopic properties of large conglomerations of the tiny invisible particles.

Newton's laws involve instantaneous action at a distance: each particle has an instantaneous effect on the motion of every other particle, no matter how distant. Newton considered this non-local feature of his theory to be unsatisfactory, but proposed no alternative. Eventually, Albert Einstein, building on ideas of James Clerk Maxwell, constructed a *local* classical theory in which all dynamical effects are generated by contact interactions between mathematical described properties localized at space-time points, and in which no effect is transmitted faster than the speed of light.

All classical-physics models of Nature are *deterministic*: the state of any isolated system at any time is completely fixed by the state of that system at any earlier time. The Einstein-Maxwell theory is deterministic in this sense, and also "local", in the just-mentioned sense that all interactions are via contact interactions between neighboring localized mathematically describable properties, and no influence propagates faster than the speed of light.

By the end of the nineteenth century certain difficulties with the general principles of classical physical theory had been uncovered. One such difficulty was with "black-body radiation." If one analyzes the electromagnetic radiation emitted from a tiny hole in a big hollow heated sphere then it is found that the manner in which the emitted energy is distributed over the various frequencies depends on the temperature of the sphere, but not upon the chemical or physical character of the interior surface of the sphere: the spectral distribution depends neither on whether the interior surface is smooth or rough nor on whether it is metallic or ceramic. This universality is predicted by classical theory, but the specific form of the predicted distribution differs greatly from what is empirically observed.

In 1990 Max Planck discovered a universal law of black-body radiation that matches the empirical facts. This new law is incompatible with the basic principles of classical physical theory, and involves a new constant of Nature, which was identified and measured by Planck, and is called "Planck's Constant." By now a huge number of empirical effects have been found that depend upon this constant, and that conflict with the predictions of classical physical theory.

During the twentieth century a theory was devised that accounts for all of the successful predictions of classical physical theory, and also for all of the departures of the predictions of classical theory from the empirical facts. This theory is called quantum theory. No confirmed violation of its principles has ever been found.

The Quantum Approach.

The core idea of the quantum approach is the seminal discovery by Werner Heisenberg that the classical model of a physical system can be considered to be an *approximation* to a quantum version of that model. This quantum version is constructed by replacing each numerical quantity of the classical model by an *action*: by an entity that acts on other such entities, and for which the order in which the actions are performed matters. The effect of this replacement is to convert each point-like particle of the classical conceptualization - such as an electron - to a smeared-out cloudlike structure that evolves in accordance with a quantum mechanical law of motion called the Schroedinger equation. This law, like its classical analog, is local and deterministic: the different elements act by contact with neighbors, and the physical state of any isolated system at any time is determined from its physical state at any earlier time.

This local deterministic quantum law of motion is, in certain ways, incredibly accurate: it correctly fixes *to one part in a hundred million* the values of some measurable properties that classical physics cannot predict.

However, this local deterministic quantum law of motion does not correctly determine human experience. For example, if the state of the universe were to have developed from the big bang solely under the control of the local deterministic Schroedinger equation then the location of the *center* of the moon would be represented in the theory by a structure spread out over a large part of the sky, in direct contradiction to normal human experience.

The smeared-out character of the position of (the center-point of) a macroscopic object, is a consequence of the famous Heisenberg Uncertainty Principle, combined with the fact that tiny uncertainties at the microscopic level usually get magnified over the course of time, *by the Schroedinger equation acting alone*, to large uncertainties in macroscopic properties.

This contradiction between a mathematical theory that is a direct mathematical generalization of classical physical theory --- and that yields many predictions of incomparable accuracy --- with the facts of everyday experience is the most basic feature of quantum theory. Its obdurate mathematical certainty allows it to serve as the fulcrum upon which rests a seismic shift in science's concept of science itself, and, in particular, of the relationship between the empirical and theoretical sides of scientific practice. To accommodate the new findings, physical science was transformed from a theory of the properties of a mechanical model of Nature that viewed us as part of the locally causal structure, distinguished from machines only by our complexity, to a theory of the relationship between the physically and psychologically described aspects of actual scientific practice.

“The Observer” and “The Observed System” in Copenhagen Quantum Theory.

The original formulation of quantum theory is called the Copenhagen Interpretation because it was created by the physicists that Niels Bohr had gathered around him in Copenhagen. A central precept of this approach is that, in any particular application of quantum theory, Nature is to be considered divided into two parts, “The Observer” and “The Observed System.” The Observer consists of the stream of consciousness of a human agent, together with the brain and body of that person, and also the measuring devices that he or she uses to probe The Observed System.

Each Observer describes himself in a language that allows him to communicate to colleagues two kinds of information: *How he has acted* in order to prepare himself - his mind, his body, and his devices - to receive recognizable and reportable data; and *What the data are* that he thereby acquires. This description is in terms of the conscious experiences of the agent. It is a description of his intentional probing actions, and of the experiential feedbacks that he subsequently receives.

In actual scientific practice the experimenters are free to choose which experiments they perform: the empirical procedures are determined by the protocols and aims of the experimenters. This element of freedom is emphasized by Bohr in statements such as:

"The freedom of experimentation, presupposed in classical physics, is of course retained and corresponds to the free choice of experimental arrangement for which the mathematical structure of the quantum mechanical formalism offers the appropriate latitude." (Bohr, 1958: 73}

This freedom is achieved in the Copenhagen formulation of quantum theory by placing the empirically/psychologically described Observer outside The Observed System that is being probed, and then subjecting only The Observed System to the rigorously enforced mathematical laws.

The Observed System is, according to both classical theory and quantum theory, describable in terms of mathematical properties assigned to points in space-time. However, the detailed forms of the laws that govern the evolution in time of this mathematical structure, and of the rules that specify the connection of this mathematical structure to the empirical facts, are very different in these two theories.

I am endeavoring here to avoid mathematical technicalities. But the essential conceptual difference between the two approaches rests squarely on a basic technical difference. This difference can be illustrated by a simple two-dimensional picture.

The Paradigmatic Example.

Consider an experiment in which an experimenter puts a Geiger counter at some location with the intention of finding out whether or not this device will "fire" during some specified time interval. The experiment is designed to give one of two possible answers: 'Yes', the counter will fire during the specified interval, or 'No', the counter will not fire during this specified interval. This is the paradigmatic quantum measurement process.

This experiment has *two* alternative mutually exclusive possible responses, 'Yes' or 'No.' Consequently, the key mathematical relationships can be pictured in a *two*-dimensional space, such as the top of your desk.

Consider two distinct points on the top of your desk called *zero* and *p*. The displacement that would move a point placed on *zero* to the point *p* is called a *vector*. Let it be called *V*. Suppose *V* has unit length in some units, say meters. Consider any two other displacements *V1* and *V2* on the desk top that start from zero, have unit length, and are perpendicular to each other. The displacement *V* can be formed in a unique way by making a (positive or negative) displacement along *V1* followed by a (positive or negative) displacement along *V2*. Let the lengths of these two displacements be called *X1* and *X2*, respectively. The theorem of Pythagoras says that $X1$ squared plus $X2$ squared is one (unity).

Quantum theory is based on the idea that the various experiencable outcomes have “images” in a vector space. The vector V1 mentioned above is the image, or representation, in the vector space of the possible outcome ‘Yes,’ whereas V2 represents ‘No.’ I will not try to describe here how this mapping of possible experiencable outcomes into corresponding vectors is achieved But the basic presumption in quantum theory is that such a mapping exists.

The vector *V* represents the state of The Observed System, which has been prepared at some earlier time, and has been evolving in accordance with the Schroedinger equation. The vector *V1* represents the state that this observed system would be known to be in if the observed outcome of the measurement were ‘Yes.’ The vector *V2* represents the state that the observed system would be known to be in if the observed result of the measurement were ‘No.’ Of course, the directions of the two perpendicular vectors *V1* and *V2* depend upon the exact details of the experiment: on exactly where the experimenters have placed the Geiger counter, and on other details controlled by the experimenters.

The outcome of the probing measurement will be either *V1* (Yes) or *V2* (No). The predicted probability for the outcome to be ‘Yes’ is *X1* squared and the predicted probability for the outcome to be ‘No’ is *X2* squared. These two probabilities sum to unity, by virtue of the theorem of Pythagoras. The sudden jump of the state from *V* to either *V1* or *V2* is called a “quantum jump.”

The crucial, though trivial, logical point can now be stated: The *orientation* of the set of “basis” vectors, *V1* and *V2,* enters into the dynamics as a *free variable* controlled by the experimental conditions, which are specified in practice by choices made by experimenters. The orientation of the set of basis vectors is thus, from a mathematical standpoint, a variable that can be, and is, specified *independently* of the state *V* of the system being probed.

This entry into the dynamics of the choices made by the experimenters is not surprising. If the experimenters are considered to stand outside, and apart from, the system being observed, as specified by the Copenhagen approach, then it is completely reasonable and natural that the choices made by the experimenters about how to probe The Observed System should be treated as variables that are independent of the variables that specify the physical state of the system they are probing.

Bohr (1958: 92, 100) argued that quantum theory should not be applied to living systems. He also argued that the classical concepts were inadequate for that purpose. So the strict Copenhagen approach is simply to renounce the applicability of *contemporary* physical theories, both classical and quantum, to neurobiology.

Von Neumann's Formulation.

The great mathematician and logician John von Neumann (1955/1932) rigorized and extended quantum theory to the point of being able to corporate the devices, the body, and the brain of the observer into the physically described part of the theory, leaving, in the psychologically described part, only the stream of conscious experiences. The part of the physically described system being directly acted upon by the psychologically described "observer" is, according to von Neumann's formulation, *the brain of that observer*. (von Neumann, 1955: 421). The quantum jump of the state of the brain of an observer to the 'Yes' basis state then becomes the representation, *in the state of that brain*, of the conscious acquisition of the knowledge associated with that answer 'Yes.' That is, the physical features of the brain state actualized by the quantum jump to the state V1 associated with the answer 'Yes' constitute the *neural correlate* of that person's conscious experience of the feedback 'Yes.'

This description of the essential dynamical structure of (von Neumann) quantum theory shows how the basic elements of the problem of the connection between mind and brain are precisely the elements that are linked together by von Neumann's dynamical equations of motion! In the first place, there is a conscious choice made by the human person about how he or she will act, or attend.

Von Neumann emphasizes the crucial importance of this first process by calling it "Process I." It specifies a particular manner of probing Nature. It fixes mathematically the orientation of the set of basis vectors – the orientation of the two vectors V1 and V2 in our two-dimensional example. This choice of orientations is causally efficacious: it enters crucially into what then happens to the physically described brain. The brain will jump to some particular one of the chosen basis vectors.

Von Neumann showed that his formulation of the theory is essentially equivalent, in practice, to the Copenhagen interpretation. But it circumvents the ad hoc separation of the dynamically unified physical world into two differently described parts, and allows the psychological description to be - as is natural - a description of a stream of conscious experiences that is closely tied to an associated sequence of physically described events in the brain.

The first key conceptual point is that von Neumann's enlargement of the physical system to include the body and brain of the observer *does not disrupt the basic mathematical structure of the theory.* In particular, it does not alter *the critical need to specify the orientation of the set of basis vectors* ---e.g., V1 and V2--- in order to make the theory work. The second key point is that this specification of basis states *continues to be undetermined by* anything in contemporary physical theory, *even when that description is extended to include the entire physical world, including the bodies and brains of the human observers.*

This lack of determination contrasts sharply to the situation in classical physics, where the incorporation of the entire physical world into the physically described system leads to *the complete determination* of the state of the brain of the observer, and hence to the complete exclusion of the consciousness of the observer from any dynamically necessary role in the determination of the flow of physical events. But in quantum theory this inclusion of the body and brain of the observer into the physically described world does not alleviate the need for Process I: the known quantum equations of motion fail to specify the choices specified by Process 1, even when all particles in the universe are included in the part of Nature described in terms of the quantum vectors. The choices on the part of the observers as to how they will act, or attend, are, *within contemporary physical theory*, “free choices.” A more elaborate theory is needed to explain or specify how these choices are made.

An Altered Perspective.

This leap by von Neumann from the realm of atomic physics to the realm of neuroscience was way ahead of its time: neuroscience was then in a relatively primitive state compared to what it is today, and had a long way to go before mainstream interest turned to the question of the connection between brains and conscious experiences. But seventy years of brain science has brought the empirical side up to the level where the details of the mind-brain relationships are being actively probed, and intricate results are being obtained that can be compared to the predictions of the psycho-physical theory prepared long ago by John von Neumann.

It is evident that a scientific approach to brain dynamics must *in principle* use quantum theory, in order to deal properly with brain processes that depend heavily on chemical and ionic processes. For example, the release of neurotransmitter from a nerve terminal is controlled by the motions of calcium ions, and these ions are small enough so that the deterministic laws of classical physics necessarily fail: quantum theory must in principle be used to describe the ion dynamics.

The chief differences at the basic conceptual level between the quantum and classical approaches to consciousness is that the classical principles make no mention of consciousness. The structure is in principle completely “bottom up.” Everything is, in principle, fully determined by what goes on at the microscopic atomic level, and any dependence of microscopic properties upon macroscopic properties, or on consciousness, is, in the end, a round-about consequence of laws expressible exclusively in terms of properties of atomic particles and the physical fields that they produce. But in quantum theory the local-deterministic (i.e., bottom-up) physical process is in principle *causally incomplete*: it fixes, by itself, neither our actions nor our experiences, nor even any statistical prediction about how we will act or what we will experience. The bottom-up process *alone* is unable to make statistical predictions, because the statistical predictions depend upon the choice of a set of basis vectors, and the bottom-up local-deterministic quantum process does not fix this choice.

This essential gap in the causal structure *not only opens the door* to the possible existence of a dynamically compatible “top-down process” governed by conscious choices, but, at least at the practical level, *entails the need for* such an extra process.

This reorganization of the dynamical structure leads to an altered perspective on the entire scientific enterprise. The psychologically described empirical side of scientific practice is elevated from its formerly subservient status - as something that needs to be *deduced* from, or constructed from, the already-dynamically-complete physical side - to the new status of co-equal dynamical partner. Science becomes the endeavor to describe the *two-way interplay* between the psychologically described empirical reality and a physically described mathematical model, rather than an attempt to deduce the existence and properties of our streams of conscious experiences from a presumed-to-be-dynamically-complete mechanical model.

Within the von Neumann framework our conscious choices control the orientations of the basis vectors. And these choices can strongly influence our actions. Thus these influences are not illusions. The theory provides a definite mechanism whereby our conscious choices, which are themselves not determined by the physically-described aspects of Nature, can significantly influence our physical actions.

Pragmatic Neuroscience.

By restricting itself to pragmatic scientific practice the Copenhagen approach was able to restrict the class of “observers” to human beings: “pigs do not do science.” Although Bohr often applied his general idea of “the lessons taught by quantum theory” to other domains of science, these applications were by way of analogy, not by way of a strict application of the specific laws of quantum theory.

Von Neumann, in his 1932 book, appeared to follow the Copenhagen idea of focusing on scientific practice. He did not address ontological questions. Those questions must be answered before any claim can be made to have created a satisfactory understanding of "the true Nature of reality." But they need not be dealt with in order to have a pragmatic scientific theory of the neurodynamics of conscious human brains: a theory that relates empirical findings to a mathematical model in a way that allows useful testable predictions to be made, and that is, moreover, philosophically and mathematically, a direct extension of the methods of atomic physics to the realm of neuropsychology.

Von Neumann's formulation of quantum theory provides the general outline of a pragmatic neurodynamics of the conscious human brain that grows naturally out of contemporary physical theory. All quantum approaches to consciousness start from this von Neumann formulation of quantum theory as the pragmatic base that provides the essential link to the empirical data. But various physicists have proposed augmenting this core structure in different ways. We turn now turn to the descriptions of a number of these proposals.

Bohr, N. (1958). *Atomic Physics and Human Knowledge.* New York: Wiley.

Bohr, N. (1963). Essays 1958/1962 on *Atomic Physics and Human Knowledge.* New York: Wiley.

Heisenberg, W. (1958). The representation of Nature in contemporary physics. *Daedalus* 87, 95-108.

Von Neumann, J. (1955/1932). *Mathematical Foundations of Quantum Mechanics.* Princeton: Princeton University Press. (Translated by Robert T. Beyer from the 1932 German original, Mathematiche Grundlagen der Quantummechanik. Berlin: J. Springer)

2. The Penrose-Hameroff Approach.

Perhaps the most ambitious attempt to create a quantum theory of consciousness is the one of Roger Penrose and Stuart Hameroff.

Their proposal has three parts: The Gödel Part, The Gravity Part, and the Microtubule Part.

The Gödel Part, which is due to Penrose, is an effort to use the famous Gödel Incompleteness Theorem to prove that human beings have intellectual powers that they could not have if they functioned in accordance with the principles of classical physical theory. Proving this would reaffirm a conclusion of the von Neumann formulation of quantum theory, namely that a conscious human being can behave in ways that a classical mechanical model cannot. Penrose's argument, if valid, would yield this same conclusion, but within a framework that relies not on quantum concepts, which are generally unknown to cognitive scientists, but rather on Gödel-type arguments, which are familiar to some of them.

The general idea of Penrose's argument is to note that, due to the mathematically deterministic character of the laws of classical physics, the output at any specified finite time of any computer behaving in accordance with the classical laws should in principle be deducible, to arbitrarily good accuracy, from a finite-step procedure based on a finite set of mutually consistent rules that encompass the laws of arithmetic. But then a human being who can be adequately modeled as a classical computer should be able to know, at any finite time, the truth *only* of those statements that can be deduced from a finite-step computation based on the finite set of rules that govern that computer. Yet Gödel-theorem-type arguments allow real mathematicians to know, given *any* finite set of consistent logical rules that encompass the laws of arithmetic, the truth of mathematical statements that cannot be deduced by any finite-step proof based on those rules. This seems to imply that a real mathematician can know things that no classical physics model of himself could ever know, namely the truth of statements that his classical computer simulation could not establish in a finite time.

Filling in the details of this argument is not an easy task. Penrose spends the better part of five chapters in "The Emperor's New Mind," (Penrose, 1989) and some 200 pages in "Shadows of the Mind" (Penrose, 1994) explaining and defending this thesis. However, the Harvard philosopher Hillary Putnam challenged Penrose's conclusion in a debate appearing in the New York Times Review of Books, (Putnam, 1994) and numerous logicians have since weighed in, all, to my knowledge, challenging the validity of Penrose's argument. Thus the Gödel Part of the Penrose-Hameroff approach cannot now be regarded as having been successfully established.

The Gravity Part of the Penrose-Hameroff approach addresses a key question pertaining to the quantum dynamics: exactly *when* do the sudden "quantum jumps" occur? In von Neumann's theory these jumps should presumable occur when the neural correlates of conscious thoughts become sufficiently well formed. But von Neumann gives no precise rule for when this happens.

The lack of specificity on this issue of precisely "*when*" is a serious liability of the von Neumann theory, insofar as it is construed as a description of the ontological mind-matter reality itself. That difficulty is the basic reason why both the original Copenhagen formulation and von Neumann's extension of it eschew traditional ontological commitments. They hew rather to the pragmatic position that the job of science is to establish useful practical relationships between empirical findings and theoretical concepts, rather than advancing shaky speculations about the ultimate Nature of reality. The pragmatic position is that theoretical ideas that optimally provide reliable practical relationships between human experiences constitute, themselves, our best *scientific* understanding of "reality." Added ontological superstructures are viewed as not true science, because additions that go beyond optimal theoretical descriptions of connections between human experiences cannot be tested empirically.

Penrose wants to provide an ontology that has "real quantum jumps." Hence he must face the issue: when do these jumps occur. He seeks to solve this problem by linking it to a problem that arises when one attempts to combine quantum theory with Einstein's theory of gravity.

Einstein's theory of gravity, namely General Relativity, is based of the idea that space-time is not a rigid flat structure, as had previously been thought, but rather a *deformable medium*, and that the way it is deformed is connected to the way that matter is distributed within it. This idea was developed within the framework of classical physical theory, and most applications of it are made within a classical-physics idealization. But serious problems arise when the quantum character of "matter" is considered. For, according to orthodox quantum theory, a particle, such as an electron or an ion, has no well defined location: its location is specified by a smeared out "probability cloud." But if the locations of the material particles are not well defined then, according to General Relativity, neither is the form of the space-time structure in which the particle structures are imbedded.

Penrose conjectures that Nature abhors uncertainty in the structure of space-time, and that when too much ambiguity arises in the space-time structure a quantum jump to some less ambiguous structure will occur. This "principle" allows him to tie quantum jumps to the amount of uncertainty in the structure of space-time.

There is no compelling reason why Nature should be any more perturbed by an uncertainty in the structure of space-time than by an uncertainty in the distribution of matter. However, by adopting the principle that Nature finds intolerable *excessive ambiguity in* the *structure of space-time* Penrose is able to propose a specific rule about when the quantum jumps occur.

Penrose's rule depends on the fact that Planck's constant gives a relationship between energy and time: this constant divided by any quantity of energy gives a corresponding interval of time. Thus if an energy associated with a possible quantum jump can be defined then a time interval associated with that potential jump becomes specified.

To identify the pertinent energy consider a simple case in which, say, a small object is represented quantum mechanically by a small cloud that divides into two similar parts, one moving off to the right, the other moving off to the left. Both parts of the cloud are simultaneously present, and each part produces *a different distortion* of the underlying spacetime structure, because matter is distributed differently in the two cases. One can compute the amount of energy that it would take to pull apart, against their gravitational attraction, two copies of the object, if each copy is located at the position specified by one of the two clouds. If one divides Planck's constant by this "gravitational energy" then a time interval associated with this distortion of space-time into these two disparate structures becomes defined. Penrose proposes that this time interval is the duration of time for which Nature will *endure* this bifurcation of its space-time structure into the two incompatible parts, before jumping to one or the other of these two forms.

This conjectured rule is based on two very general features of Nature: Planck’s universal constant of action and the Newton-Einstein universal law of gravitation. This universality makes the rule attractive, but no reason is given why Nature must comply to this rule.

Does this rule have any empirical support?

An affirmative answer can be provided by linking Penrose’s rule to Hameroff’s belief that consciousness is closely linked to the *microtubular sub-structure of the neurons.*

It was once thought that the interiors of neurons were basically structureless fluids. That conclusion arose from direct microscopic examinations. But it turns out that in those early studies the internal substructure was wiped out by the fixing agent. It is now known that neurons are filled with an intricate structure of *microtubules*.

Each microtubule is a cylindrical structure that can extend over many millimeters. The surface of the cylinder is formed by a spiral chain of tubulin molecules, with each circuit formed by thirteen of these molecules. The tubulin molecule has molecular weight of about 110,000 and it exists in two slightly different configurational forms. Each tubulin molecule has a single special electron that can be in one of two relatively stable locations. The molecule will be in one or the other of the two configurational states according to which of these two locations this special electron is occupying.

Hameroff is an anesthesiologist, and he noted that there is close correspondence between, on the one hand, the measured effects of various anesthetics upon consciousness and, on the other hand, the capacity of these anaesthetics to diminish the ability of the special electron to move from one stable location to the other. This suggests a possible close connection between consciousness and the configurational activity of microtubules.

This putative linkage allows an empirical test of Penrose's rule to be made.

Suppose, in keeping with the case considered by Penrose, you are in a situation where one of two possible experiences will probably occur. For example, you might be staring at a Necker Cube, or walking in a dark woods when a shadowy form jumps out and you must choose "fight" or "flight," or perhaps you are checking your ability to freely choose to raise or not raise your arm. Thus one of two alternative possible experiences is likely to occur. Various experiments suggest that it takes about half a second for an experience to arise. Given this time interval, Penrose's formula specifies a certain corresponding energy. Then Hameroff can compute, on the basis of available information concerning the two configurational states of the tubulin molecule, how many tubulin-molecule configurational shifts are needed to give this energy.

The answer is about 1% of the estimated number of tubulin molecules in the human brain. This result seems reasonable. Its reasonableness is deemed significant, since the computed fraction could have come out to be perhaps billions of times smaller than, or billions of times greater than, 100%. The fact that the computed value is "in the ballpark" supports the idea that consciousness may indeed be closely connected to tubulin configurational activity.

Given this rather radical idea – it was previously thought that the microtubules were merely a construction scaffolding for the building and maintenance of the physical structure of the neurons – many other exotic possibilities arise. The two configurational forms of the tubulin molecule mean that it can hold a "bit" of information, so maybe the microtubular structure forms the substrate of a complex *computer* located within each neuron, thus greatly expanding the computational power of the brain. And maybe each such computer is in fact a "quantum computer." And maybe these quantum computers are all linked together to form one giant brain-wide quantum computer. And maybe these hollow micro-tubes form wave guides for quantum waves.

These exotic possibilities are exciting and heady ideas. They go far beyond what conservative physicists are ready to accept, and far beyond what the 1% number derived from Penrose's rule actually supports. What is supported is merely a connection between consciousness and microtubular activity, *without the presence* of the further stringent *coherence conditions* required for the functioning of a quantum computer.

"Coherence" means preservation of the "phase" relationships that allow waves that have traveled via different paths to come back together so that, for example, crest meets crest and trough meets trough to build an enhanced effect. Quantum computation requires an effective isolation of the quantum informational waves from the surrounding environment, because any interaction between these waves and the environment tends to destroy coherence. But the required isolation is difficult to maintain in a warm, wet, noisy brain.

The simplest system that exhibits a behavior that depends strongly on quantum interference effects, and for which the maintenance of *coherence* is essential, is the famous "double-slit experiment." When photons of a single wave length are allowed to pass, one at a time, through a pair of closely spaced narrow slits, and are later detected by some suitable detection device, one finds that *if the photonic system is not allowed to perceptibly influence any environmental degree of freedom* on its way to the detection device then the pattern of detected events depends on an *interference* between the parts of the beam passing through the two different slits. This pattern is very different from what it is if the photon is allowed to perceptibly disturb, the surrounding environment. Disturbing the environment produces a "decoherence" effect, i.e., a weakening or disappearance of the interference effects.

If a system interacts with its environment, it is difficult to prevent a "perceptible influence." If even *one* of the thousands of particles in the environment is displaced by a discernible amount then the coherence is lost, and the quantum interference effect will disappear.

Since the medium in which the putative quantum information waves are moving involves different conformational states of huge tubulin molecules of molecular weight ~110,000, it would seemingly be exceedingly hard to ensure that the passage of these waves will not disturb even one particle of the environment by a discernible amount.

Max Tegmark wrote an influential paper in Physical Review E. It mathematically buttressed the intuition of most physicists that the macroscopic coherence required by Penrose-Hameroff---namely that the microtubular conformal states can form the substrate of a quantum computer that extends over a large part of the brain--- could not be realized in a living human brain. Tegmark concluded that the coherence required for macroscopic quantum computation would be lost in a ten trillionth of a second, and hence should play no role in consciousness. This paper was widely heralded. However, Hagan, Hameroff, and Tuszynski wrote a rejoinder in a later issue of the same journal. They pointed out several departures of Tegmark's assumptions from those of the Penrose-Hameroff model. The associated corrections lengthened the coherence time by 8 or 9 orders of magnitude, thus bringing the situation into a regime where the non-equilibrium conditions in a living brain might become important: energetic biological processes might conceivably intervene in a way that would make up the still-needed factor of ten thousand. However, the details of how this might happen were not supplied. Hence the issue is, I believe, still up in the air, with no detailed explanation available to show how the needed macroscopic quantum coherence could be maintained in a living human brain.

It must be stressed, however, that these exotic "quantum computer" effects are not necessary for the emergence of strong quantum effects within the general framework supplied by the combination of Penrose's rule pertaining to gravity and Hameroff's claim concerning the importance of microtubules. According to von Neumann's general formulation, the state of the brain - or of the microtubular part of the brain - is adequately represented by what physicists call the "reduced density matrix" of that subsystem. This representation depends only on the variables of that subsystem itself – i.e., the brain, or microtubular array - but nevertheless takes adequate account of the interactions of that system with the environment. It keeps track of the quantum coherence or lack thereof. Penrose's rule can be stated directly in terms of the "reduced density matrix," which displays, ever more clearly as the interaction with the environment grows, the two alternative states of the brain – or of the microtubular array – that Nature must choose between. This reduced density matrix representation shows that the powerful decoherence effect produced by strong interactions with the environment actually *aids* the implementation of Penrose's rule, which is designed to specify *when* the quantum jump occurs (and perhaps to which states the jump occurs). The capacity of the brain to be or not to be *a quantum computer* is a very different question, involving enormously more stringent conditions. It thus is important, for logical clarity, to separate these two issues of the requirements for *quantum computation* and for *quantum jumps*, even though they happen to be interlocked in the particular scenario described by Penrose and Hameroff,

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Hagen, S., Hameroff, S, & Tuszynski, J. (2002). Physical Review E65, 061901-1 – 061901-11.

Hameroff, S. & Penrose, R. (1996). Orchestrated reduction of quantum coherence in brain microtubules: a model for consciousness. J. Consciousness Studies 3, 36-53.

Penrose, R. (1986). *The emperor's new mind*. New York: Oxford.

Penrose, R. (1994). *Shadows of the mind*. New York: Oxford.

Putnam, H. (1994). Review of Roger Penrose, Shadows of the Mind, *New York Times Book Review*, November 20, p.7. Reprinted in AMS bulletin:
www.ams.org/journals/bull/pre-1996data/199507/199507015.tex.html

Tegmark, M. (2000). Importance of quantum decoherence in brain process. *Physical Review* E61, 4194-4206.

3. The Bohm Approach.

The Copenhagen and von Neumann formulations of quantum theory are non-deterministic. Both specify that human choices enter into the dynamics, but neither specifies the causal origins of these choices. The question thus arises: what determines these choices?

One possibility is that these choices arise in some yet-to-be-specified way from what we conceive to be the *idealike aspect of reality*. That option was pursued by Penrose, with his suggestion that our thoughts are linked to Plato's world of ideal forms. Another – seemingly different – possibility is that there is a *more complete physical description* that involves physically described entities that are different from the smeared out structures of the orthodox formulations, and that these *other physical elements* determine the features left undetermined by the orthodox formulations.

This second approach was developed by David Bohm (1952, 1993). His formulation of quantum theory postulates, in effect, the existence of the old-fashioned world of classical physical theory. This classical-type world is supposed to exist in *addition to the wave function of quantum theory* and, like that wave function, it evolves in a way completely determined by what precedes it in time. This theory reinstates determinism in a way compatible with the predictions of quantum theory, but at the expense of abandoning locality: Bohm's theory entails strong, long-range, instantaneous action-at-a-distance.

One serious failing of Bohm's approach is that it was originally formulated in a non-relativistic context, and has not yet – after half a century and great effort – been extended to cover the most important domain in physics, namely the realm of quantum electrodynamics. This is the theory that covers the atoms that make up our bodies and brains, along with the tables, chairs, automobiles, and computers that populate our daily lives. This deficiency means that Bohm's theory is, at present, primarily a philosophically interesting curiosity, not a practically useful physical theory.

Also, Bohm's theory, at least in its original form, is not really germane to the issue of consciousness. For Bohm's theory *successfully achieved its aim,* which was precisely to get rid of consciousness: i.e., to eliminate consciousness from the basic dynamical equations, just as classical physics had done.

Bohm recognized, later on, that some understanding of consciousness was needed, but he was led instead, to the notion of an infinite tower of mechanical levels, each controlling the one below, with consciousness somehow tied to the mystery of the infinite limit. (Bohm, 1986, 1990) This infinite-tower idea tends to diminish the great achievement of the original theory, which was to reinstate physical determinism in a simple way.

To examine this conceivable option of a *complete physical determinism compatible with the empirical predictions of quantum theory* it is instructive to examine Bohm's original deterministic model in order to see how, within that deterministic consciousness-free framework, consciousness nevertheless enters, effectively, at the level of scientific practice.

As explained in the introductory section, scientific practice involves setting up experimental conditions that promote consciously conceived objectives. In von Neumann's theory these consciously chosen actions influence the subsequent course of events in The Observed System, which, according to von Neumann's version of quantum theory, is primarily the brain of the human participant. A key point is that these choices, made by the experimenter about how he or she will act, are treated in von Neumann's theory, and also by Copenhagen quantum theory, as *input data*, to be fixed by the experimenter. These choices are *treated* as free, controllable and knowable, input boundary conditions.

In Bohm's theory these choices are not *actually* free: freedom is an illusion. The apparently free choice is, at a deeper dynamical level, completely determined by *physical* conditions, just as it was in classical physics. However, the putative existence of this deeper dynamical underpinning does not subvert or displace the quantum dynamics. The analysis of Heisenberg shows that, even within the context of Bohmian mechanics, the human observers can never determine, or *know*, to which of the conceivable, logically possible classical Bohmiam worlds their experiences belong. The Heisenberg Uncertainty Principle cannot be evaded. The most that experiencers can ever actually ***know*** about the Bohmian classical world of which they are a putative part is represented by a quantum wave function.

This limitation *in human knowledge* is acknowledged by Bohm. Indeed, Bohm's theory leaves scientific practice the same as it is in the Copenhagen approach. This *equivalence at the practical level* of Bohm's model to the Copenhagen formulation means that, in actual practice, the unfillable gap in human knowledge mandated by the uncertainty principle is bridged by reverting to Copenhagen quantum theory. That orthodox statistical theory is used to replace the *in principle unknowable and uncontrollable information about the supposedly deterministic microscopic realities* by *in-practice controllable realities*, namely our human conscious choices about which actions we will take (i.e., which experiments we will perform), and in-practice knowable realities, namely our experiences about the outcomes of these experiments.

The important point here is that the details of the Bohmian microstructure can, as a matter of principle, never be known to us, and hence cannot be used to make predictions. But we can and do experience the immediate consequences of our conscious choices about how to act, *and these experiential feedbacks place conditions on the putative Bohmian microstructure*.

For example, if it is assumed that our experiences are at least compatible, within the limitations imposed by the uncertainty principle, with the positions and motions of the atoms of the postulated-by-Bohm-to-exist classical world, then we can deduce, from our observations, whether this postulated classical world is in the part of space corresponding to the quantum wave packet associated with "Yes, the Geiger counter did fire," or is it in the part of space corresponding to the wave packet associated with "No, the Geiger counter did not fire." This partial information, expressible in terms of quantum wave functions, will allow us, by using quantum theory, to make predictions about our future experiences.

Thus controllable and knowable input conditions entail *statistical* consequences in the realm of subsequent human experiences, and these consequences can be computed by using the quantum mechanical equations. These equations allow us to make apparently optimal predictions about knowables without needing to know anything about the unknowable Bohmian micro-substructure, beyond what is specified by quantum mechanics,

The bottom line is that, *even within the context of the deterministic Bohmian theory, it is the quantum rules that constitute the useful scientific tools,* because they allow us, without needing to know anything about the in-principle-unknowable classical idealizations, to make predictions pertaining to what we can know. This conclusion will apparently continue to be true in the context of *any* deterministic theory that is *compatible with* the statistical rules of quantum theory. This is the essential basis of the Copenhagen claim the orthodox theory is scientifically (i.e., pragmatically) complete, in spite of disclaimers about “what is really going on.”

When solving a problem in physics there is always a question about which variables to use. At the level of practical science it seems advantageous to use variables that are controllable and knowable in actual practice rather than ones that are unknowable in principle. Why bring unknowable parameters into science when we have equations in terms of controllable/knowable parameters that, according to the unchallenged arguments of Heisenberg and Bohr, tell us all that we can ever determine (within the framework of science) about what is knowable?

The advantages of using equations involving controllable and knowable parameters rather than unknowable ones are just as real in neuroscience as they are in atomic physics. Of what use are (highly nonlocal) deterministic equations that depend on the in-principle-unknowable motions of classically conceived calcium ions inside nerve terminals, instead of variables that that represent our knowledge about our controllable actions and their experienced feedbacks along with what quantum theory asserts to be the generalization of classical physics that provides a foundation of all physical-type information about the brain that can ever be known or used to make predictions about what can be known?

Bohm, D. (1952). A suggested interpretation of quantum theory in terms of hidden variables. *Physical Review,* 85, 166-179.

Bohm, D. J. (1986). A new theory of the relationship of mind to matter. *The Journal of the American Society for Psychical Research,* 80, 113-135.

Bohm, D. J. (1986). A new theory of the relationship of mind to matter. *Philosophical Psychology*, 3, 271-286.

Bohm, D, & Hiley, D.J. (1993). *The Undivided Universe.* London and New York: Routledge.

4. The von Neumann/Stapp Approach

Von Neumann converted Copenhagen quantum theory, in a series of steps, into a form in which the entire physical universe, including the bodies and brains of the conscious human participant/observers, is represented by the basic quantum state, which is called the state of the universe. The state of any subsystem, such as a brain, is formed by averaging (tracing) this basic state over all variables *other* than those that describe the state of that subsystem. The dynamics consists of *three* processes.

Process **1** is the choice on the part of the experimenter about how to act. This choice is sometimes called "The Heisenberg Choice," because Heisenberg strongly emphasized its crucial role in quantum dynamics. At the pragmatic level it is a "free choice," because it is controlled in practice by the conscious intentions of the experimenter/participant, and neither the Copenhagen nor von Neumann formulations provide any description of the *causal origins* of this choice, apart from the mental intentions of the human agent. Each intentional action involves an effort to produce a conceived experiential feedback, which can be an immediate confirmation of the success of the action, or a delayed monitoring of the experiential consequences of the action.

Process **2** is the quantum analog of the equations of motion of classical physics. As in classical physics, these equations of motion are local --- i.e., all interactions are between immediate neighbors --- and deterministic. They are obtained from the classical equations by a certain *quantization* procedure, and are reduced to the classical equations by taking the *classical approximation* of setting to zero the value of Planck's constant everywhere it appears. Evolution via the quantum Process **2** normally has the effect of expanding the microscopic uncertainties demanded by the Heisenberg Uncertainty Principle into the macroscopic domain: the *centers* of large objects tend to become diffused over large regions. The disparity between this Process-**2**-generated theoretical indefiniteness and the consciously experienced definiteness of the positions of visible objects is resolved by invoking Processes **1** and **3**.

Process **3** is sometimes call the “Dirac Choice.” Dirac called it a “choice on the part of Nature.” It can be regarded as Nature’s answer to the question posed by Process **1**. This posed question might be: Will the detecting device be in the state that signifies “Yes, a detection has occurred” ? Or, “Will the Geiger counter be observed to ‘fire’ in accordance with the experiential conditions that define a `Yes’ response?” Each Process **3** reply must be preceded by a Process **1** question.

Process **1** brings the conscious choices made by the observer/participant directly into the dynamics. On the other hand, there is a tendency for the effect of the choices of the questions on the state of observed system to be washed out, in the long run, by the averaging over the two possible answers, `Yes’ and ‘No.’ However, it has been pointed (Stapp, 1999) out that if willful effort can sufficiently control the *rate* at which a sequence of similar Process 1 events occur then the course of brain events can be strongly effected by the mental action. The rapid sequence of question-answers can, by virtue of the quantum laws, hold a particular “template for action” in place, against the normal physical forces. The prolongation of the activation of this pattern of brain activity can tend to produce the intended bodily action, in accordance with William James’s “ideo-motor” theory of action (James, 1890: 522)

This “holding effect” of a rapid sequence of similar Process **1** events is an automatic consequence of the quantum laws of motion, and it has been extensively studied by quantum physicists, both empirically and theoretically, under the title “The Quantum Zeno Effect.”

This quantum account of the origin of the causal efficacy of conscious will (effort) corresponds closely to the ideas of William James, as is made evident by the following quotations:

``Thus we find that we reach the heart of
our inquiry into volition when we ask by
what process is it that the thought of any

given action comes to prevail stably in the
mind." (James, 1890:564)

and later

``The essential achievement of the will, in short, when it is most `voluntary,' is to attend to a difficult object and hold it fast before the mind. ... Effort of attention is thus the essential phenomenon of will."

Still later, James says:

``Consent to the idea's undivided presence, this is effort's sole achievement."...
``Everywhere, then, the function of effort is the same: to keep affirming and adopting the thought which, if left to itself, would slip away."

The important conclusion is that the apparent capacity of conscious effort to influence physical actions, which seems so puzzling and necessarily illusory within classical physics, is naturally explainable within quantum theory as a direct causal consequence of the laws of motion. Because these willful choices are unspecified "free variables" within the framework of contemporary quantum theory, one can say, accurately, that within contemporary physics a person's "free will" can influence his or her physical actions.

This leads to the question: What causes our mental choices to be what they are?

The *classical-physics-based* response is to affirm the belief – or faith – that the cause is completely describable in *micro-local* terms: in terms of essentially mechanical contact interactions between tiny physical elements. But this faith is not based on science! Science tells us that the old micro-local classical ideas *cannot be correct*. Consequently, there is no *rational* reason to insist, *on the basis of science*, that the cause of the feeling of effort must be describable microlocally. Idea-like qualities are certainly parts of reality, and there is no evidence from science that they cannot be *irreplaceable* components of the causal chains that connect our experiences to each other. Contemporary basic physical theory explicitly introduces our conscious choices about how to act into the laws of change and motion. It is counterproductive, at least at the level of practical science, to eliminate these controllable and knowable variables in favor of idealized concepts that are known to be false and involve variables that are unknowable in principle. And it is reasonable to suppose that mental realities, such as feelings and ideas and thoughts, contribute to the determination of the mental choices that enter into Process 1. An integrated neuropsychological theory that builds upon the ontologically incomplete quantum theory will presumably be the next step.

This tripartite quantum dynamics involving Choice, Causation, and Chance (Processes **1**, **2**, & **3**, respectively) and the implementation of Will (Volition) via the conscious control of the rapidity of Process **1** events, provides the foundation of a quantum approach to neuro-psychology. But how well does this quantum approach work in actual practice?

The Pashler Data

A great deal of experimental work in the field of The Psychology of Attention is summarized in Harold Pashler's recent book of that title [Pashler, 1998].

Pashler organizes his discussion by separating perceptual processing from post-perceptual processing. The former covers processing that, first of all, identifies such basic properties of stimuli as location, color, loudness, and pitch, and, secondly, identifies stimuli in terms of categories of meaning. The post-perceptual process covers the tasks of producing motor and cognitive actions beyond mere categorical identification. Pashler emphasizes [p. 33] that ``the empirical findings of attention studies specifically argue for a distinction between perceptual limitations and more central limitations involved in thought and the planning of action." The existence of these two different processes, with different characteristics, is a principal theme of Pashler's book. [pp. 33, 263, 293, 317, 404.] He argues that the former processes are carried out in parallel, but that the latter processes, which seem to require effortful choosing, operate in series, and have a capacity that, although limited, can often be enlarged by willful effort.

Pashler's conclusion is based on the analysis of a huge array of recent experiments. But the central finding is succinctly illustrated in a finding dating from the nineteenth century, namely that mental exertion reduces the amount of physical force that a person can apply. He notes that ``This puzzling phenomena remains unexplained.'' [p. 387]. However, if we take the sequence of Process I events associated with an agent to have a limited "capacity" in terms of events per second, then this effect is a natural consequence of quantum theory: creating a physical force by muscle contraction requires a *conscious effort* that prolongs the existence of the neural template for action that opposes the Process-**2**-generated tendency of the brain to evolve toward a more relaxed state. This prolongation is produced by the Quantum Zeno Effect, and its effect is roughly proportional to the number of bits per second of central processing capacity that is devoted to the task. So if part of this processing capacity is directed to another task, then the applied force will diminish.

This example is just one simple case, but it illustrates the general principle. The identification of Pashler's limited central serial "capacity" with the rate of occurrence of Process **1** events, assumed to be increasable by willful effort, up to a limit, appears to explain the general features of all of the many diverse empirical results cited by Pashler in support of his thesis. (Stapp, 2001)

The apparent success of this quantum psychophysical theory in accounting for Pashler's data does not mean that classical physics could not be supplemented in some ad hoc way that would enable it to match that performance. However, the von Neumann theory allows the data to be explained directly in terms of *the already existing explicitly described tripartite process that constitutes the core of contemporary basic physical theory*, whereas an explanation based on classical physics is predicated on the untenable idea that the classical concepts of causation can be extrapolated from the motions of planets and falling apples to the motions of ions inside nerve terminals. It also rests on a theory that is not only demonstrably false, but is dynamically and logically complete without entailing the existence of a part of reality that we know does exist, namely human consciousness. In contrast, von Neumann's equations specify definite dynamical connections between consciousness and brain activity, and they do so in a theoretical framework that automatically entails all of the valid predictions of classical physics. So what is the rationale, in neuro-psychology, for rejecting the fundamental equations of contemporary physics, which incorporate consciousness, and explain all of the valid classical features of phenomena, in favor of classical concepts that are known to be fundamentally false and that leave consciousness out?

The Libet Data

Perhaps the best way to understand the essence of the quantum approach to consciousness is to see how it applies to the famous Libet experiments pertaining to willful action. (Libet, 2003)

The "problem" with the Libet data is that when an action is 'willed'– such as 'willing' a finger to rise– a readiness potential (RP) appears *before* the experience of 'willing' appears. Libet explains this by saying that the conscious choice to perform this action does not occur until the state of readiness is in place: the conscious choice is simply to "Veto" or "Consent To" a specified action, whose physical 'template for action' is already in place, imbedded in a particular pattern of neural activity.

In the explanation of quantum theory that follows I shall introduce some symbols and equations. Non-physicists can regard each of these as just a pictorial representation of the corresponding idea that I describe in words, together with the promise that this picture, in the minds of physicists, encodes a definite mathematical procedure.

Quantum theory is based on Heisenberg's discovery that the empirical facts of physics (many of which are logically incompatible with the basic precepts of classical physics) can be described by a new theory, quantum theory, which can be constructed by replacing the "numbers" in classical physics by "actions" (operators). A temporal sequence of actions is represented by a sequence of

corresponding symbols, written, say from right to left. In special cases the action is simply multiplication by a number. In those cases the order of applying the actions does not matter: ab=ba. But in the general case the order does matter: (ab-ba) is not zero.
The difference between quantum physics and its classical approximation resides in certain of these differences that are proportional to Planck's constant. Setting those differences to zero give the classical approximation. Thus quantum theory is closely connected to classical physics, but is incompatible with it: nonzero quantities must be set to zero to obtain classical physics.

In von Neumann's theory --- in which the entire physical universe is included in The Observed System, and the brain is the system being directly acted upon or probed by the psychologically described Observer --- the dynamics of this brain depends critically upon an essential correspondence between certain actions/operators that act on the state of the brain and associated human experiences. Each such action is represented by a "projection operator" P, which satisfies PP=P. (The double action PP of a projection operator P has the same effect as a single action P.) If the experience is labeled by 'e' then the associated projection operator is represented by P(e). In von Neumann's formulation of quantum theory this operator P(e) acts upon the state of the brain of the observer/participant/agent and specifies *the neural correlate* of the experience 'e.'

The mappings P(e) specify a mind-to-matter correspondence that plays a key role in the dynamics of the brain of a conscious agent. In particular, each experience must be proceeded by a choice of some particular P(e), and of a time t. The basic equation of quantum theory then asserts that the state at time t of the observed system, which is represented by an action/operator S(t) will suddenly jump either to the state S'(t) =P(e) S(t) P(e), or to the state S''(t) = (1-P(e)) S(t) (1-P(e)), and the probability that jump will be to S'(t) is Trace S'(t)/Trace S(t). The analogous formula holds for S''(t).

[If A is an action/operator then Trace A is a *number* that is generated by performing a certain kind of quantum averaging process on A. Normally an operator "acts on" the operator that stands to its right. But the rightmost operator in a chain can also act back around on the left-most operator of that chain, like a snake biting its own tail. This

produces the "Trace" of that *chain* of operators, which is itself one single operator. The connection of the mathematical formulas to measurable numbers is always given by this Trace operation.]
The state S'(t) is the part of S(t) that contains the neural correlates of the conscious experience e, and S''(t) is the part of S(t) that survives if the possible experience e does not occur at time t.

Any adequate theory of the connection between the stream of consciousness and the brain processes of the conscious agent must involve connections between conscious events and associated patterns of brain/neural activity. These are the so-called "neural correlates of consciousness," the NCC's. But the technical differences between classical theory and quantum theory render the role of the NCC's in the causal structure very different in these two theories. In classical theory the NCC's are supposed to be wholly described and determined by atomic-level process in the brain, and the conscious events are either causally inert by-products of brain activity that have no influence back on physical processes, which are fixed without referring to them, or they are, precisely, certain (complex) properties or attributes of a person's classically describable brain activity. In both cases, the person's conscious experiences play no essential causal role in the determination of his actions: the causal chain can in principle be described wholly in terms of classically describable atomic process, with no reference to "feelings" or "ideas" or "thoughts." In sharp contrast, a person's conscious choices enter *irreplaceably* into the quantum dynamics as "free input variables" that replace the perhaps nonexistent but in any case unknowable-in-principle classically conceived atomic parameters. Since nothing in contemporary quantum theory fixes the conscious choices, which, however, have strong effects on the physically described properties of the brain, it is completely possible that these "free" choices will be strongly influenced by psychologically described realities, such as thoughts, ideas, and feelings.

The assumption that ties quantum theory naturally to the psychophysical data, and to William James ideo-motor theory, is that Willful Effort is associated with a state P(e)S(t)P(e) of the brain that causes the question associated with P(e) to occur rapidly on the time scale of the change of P(e)S(t)P(e), thereby activating the Quantum

Zeno Effect, which will keep P(e)S(t)P(e) large much longer than would otherwise be the case. This part of the state is considered to represent a certain "template for action," which is, by virtue of the basic quantum equations of motion and change, held in place by the rapid posing of the same question.

In the Libet experiment the original commitment by the subject to, say, "raise my finger within the next minute" will condition his brain to produce a sequence of potential RP's distributed over the next minute. When the brain activity associated with one of these RP's reaches a certain prominence the Process **1** action associated with P(e), with e the experience of "raising the finger," will occur. Because the commitment is spread over a minute the probability that Nature's answer will be `Yes' will be very small for each individual RP in the sequence. Hence most of the possible RP's in the sequence will not be actualized: they will be eliminated by the `No' answer on the part of Nature. But for one of these Process **1** events the associated Process **3** will deliver the answer "Yes," and the associated experience e will occur. In order to be efficacious the experience e must contain an element of will, which will cause the Process **1** associated with this P(e) to occur quickly again, activating the Quantum Zeno Effect. The finger-raising template for action will thus be held in place, and this will cause the finger to rise.

In this scenario the `Yes' experience of willing the finger to rise occurs *after* the beginning of the build-up of the associated readiness potential, just as Libet says. This readiness potential is actualized by Nature's first `Yes' answer. None of the "potential readiness potentials" associated with the `No' answers to the earlier Process **1** events will have been actualized. So the physical situation actualized by the `Yes' answer at time t will actualize a physical situation that includes a readiness potential that has already begun its build up before time t. But even after this actualizing experience at t there is still time to block the action by cutting off the sequence of events needed to initiate the action: a 'veto' can occur.

It might seem that this occurrence of the build up of the readiness potential *before the experience that actualizes it* might violate causality requirements. But the computations of orthodox quantum theory show that this kind of precursor activity *cannot be controlled* in such a way as to, say, send a controlled message backward in time. The event is controlled by the Process **3** choice (Nature's choice) to say `Yes' at time t, not before. This leads, in the end, to the conclusion that this effect cannot be used to send a (controllable) signal backward in time.

Applications in Neuropsychology and Neuropsychiatry

This theory has been applied in both Neuropsychology and Neuropsychiatry. In the former case (Oschner, 2002; Schwartz, 2003) human subjects are first instructed how to alter their mental reactions to emotionally-charged visual stimuli by adopting certain mental strategies. Then their reactions to such stimuli are studied using fMRI under differing choices of mental set. The brain scans reveal profoundly different patterns of response to the stimuli according to the strategy chosen by the subject.

The key *empirical* input variables here are the willful choices by the human subject about how he or she will (mentally) act. The von Neumann theory provides a physics-based framework for analyzing the data in terms of these input parameters, without being limited by the idea that basic science requires all psychogenic causes to be explained by classically conceived physiological causes. Indeed, quantum theory says that micro-local explanations of brain dynamics in terms of the concepts of classical physics are impossible in principle, and suggests that willful choices about how to act be treated as the pertinent causally efficacious psychogenic basic input parameters, in line with the way that the controllable and knowable choices made by human beings are treated as basic inputs in quantum theory. The notion that such parameters need to be explained within the conceptual framework of classical physics is not rationally supportable.

In the psychiatric cases (Schwartz, 2002) the effectiveness of communication between therapist and patients was enhanced by teaching the patients that quantum theory refutes the claim of classical physics, and of medical orthodoxy, that the body-brain is a machine, and that the felt power of conscious will is sheer illusion.

Also, brain scans of patients are used as empirical evidence of the therapeutic value of properly directed willful conscious control of attention. Therapy is aided by insisting that acts of Will function as a force in Nature that has the capacity to oppose and overpower the physically based forces. This thesis can be strongly supported within von Neumann quantum theory. (Stapp, 1999)

The key elements of the theory are the NCC's, which are specified by the projection operators P(e). But how is this mapping between the two conceptually disparate regimes established? The answer is by trial and error empirical testing of the correspondence between the feeling of the conscious effort and the feeling of the experiential feedback. Every healthy alert infant is incessantly engaged in mapping out the correspondences between efforts and feedbacks, and he/she builds up over the course of time a repertoire of correspondences between the feel of the effort and the feel of the feedback. This is possible because different effortful choices have, according to the quantum equations, different physical consequences, which produce different experiential consequences. This whole process of learning would appear to depend crucially upon the actual causal efficacy of chosen willful efforts: if efforts have no actual consequences then how can learning occur, and the fruits of learning be applied?

The focus here has been on the theoretical foundations of pragmatic scientific practice. However, the von Neumann theory lends itself also to ontological interpretation.

The essential change from classical theory is that the classical state of the universe represents a purported *material* realty, whereas the von Neumann quantum state of the universe represents a purported *informational* reality. This latter reality has certain matter-like features: it can be represented in terms of micro-local entities (local quantum fields) that *usually* evolve by direct interactions with their neighbors. But the von Neumann quantum state represents the collective knowledge of all agents, and it changes whenever the knowledge of any agent changes. Thus the "physical reality" represented by the quantum state has the idealike quality of a representation of knowledge. Like knowledge its representation of faraway things can instantly change when we acquire here knowledge of something known to be correlated to the faraway things. Moreover, it represents possibilities, potentialities, and probabilities, which seem to be idealike qualities.

I have not gone into these ontological issues here. I mention them now only to emphasize that in the construction of a quantum-based neuropsychology the clear separation between mind and matter that underlies classical physics will be dissolved by the replacement of classical concepts by quantum ones.

It should be mentioned that everything said about the von Neumann theory is completely compatible with there being very strong interactions between the brain and its environment: the state S(t) of the brain is what is known as the statistical operator (reduced density matrix) corresponding to the brain. It is formed by averaging (tracing) over all non-brain degrees of freedom, and automatically incorporates all of the decoherence effects arising from interactions with the environment.

Von Neumann's theory provides a general physics-based psycho-physical framework. We now turn to efforts to tie it to the detailed structure of the brain.

Libet, B (1985). Unconscious cerebral initiative and the role of conscious will in voluntary action. *Behavioural & Brain Sciences*, 8, 529-566.

Libet, B. (2003). Cerebral physiology of conscious experience: Experimental Studies. In N. Osaka (Ed.), *Neural Basis of Consciousness*. [Advances in consciousness research series, 49] Amsterdam & New York: John Benjamins.

Ochsner, K.N. & Silvia A. Bunge, James J. Gross, and John D.Gabrieli (2002). Rethinking feelings: An fMRI study of the cognitive regulation of emotion. *J. Of Cognitive Neuroscience,* 14:8, 1215-1229.

Pashler, H. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.

Schwartz, J. & Begley, S. (2002). *The mind and the brain: neuroplasticity and the power of mental force*. New York: Harper-Collins.

Schwartz, J., Stapp, H. & Beauregard, M (2003). The volitional influence of the mind on the brain, with special reference to emotional self regulation. In M. Beauregard (Ed.), *Consciousness, Emotional Self-Regulation and the Brain*. [Advances in Consciousness Research Series]. Amsterdam & New York: John Benjamins.

Stapp, H. (1999). Attention, intention, and will in quantum physics. J. Consciousness Studies, 6, 143-164.

Stapp, H. (2001). Quiantum theory and he role of mind in Nature. *Found. Phys*. 31, 1465-1499.

James, W. (1890) *The principles of psychology Vol. II*. New York: Dover.

5. The Eccles-Beck Approach.

Sir John Eccles suggested in 1990, in the Proceedings of the Royal Society (Eccles 1990), that quantum theory plays a key role in the workings of the conscious brain. Based in part on his discussions with Henry Margenau (See Margenau 1984), Eccles noted that the statistical element in quantum theory allows an escape from the rigid determinism of classical physics that has plagued philosophy since the time of Isaac Newton. In his later book "How the self controls its Brain" Eccles (1994) notes that , "There is of course an entrenched materialist orthodoxy, both philosophic and scientific, that rises to defend its dogmas with a self-righteousness scarcely equaled in the ancient days of religious dogmatism." He says at the outset that, "Following Popper (1968) I can say:

I wish to confess, however, at the very beginning, that I am a realist: I suggest somewhat like a naïve realist that there is a physical world and a world of states of consciousness, and that these two interact."

Eccles gives "two most weighty reasons" for rejecting the classical-physics-based concept of materialism. (Eccles 1994, p,9) First, classical physics does not entail the existence or emergence of the defining characteristic of consciousness, namely "feelings," and hence entails no theory of consciousness. Second, because the Nature of the mapping between brain states and states of consciousness never enters into the behavior of an organism, there is no evolutionary reason for consciousness to be closely connected to behavior, which it clearly is.

Eccles' approach to the mind-brain problem has three main points. The first is that consciousness is composed of elemental mental units called psychons, and that each psychon is associated with the activation of a corresponding macroscopic physical structure in the cerebral cortex that Eccles calls a *dendron*. It is anatomically defined, and is connected to the rest of the brain via a large number of synapses.

The second point is the claim that quantum theory enters brain dynamics in connection with exocytosis, which is the release of the contents of a "vesicle" – filled with neurotransmitter – from a nerve terminal into a synaptic cleft.

The third point is a model developed by the physicist Friedrich Beck that describes the quantum mechanical details of the process of exocytosis.

The first claim, that psychological processes have elemental units associated with dendrons, places Eccles' theory somewhat apart from those who have suggested that *the electromagnetic field* in the brain might serve as the carrier of the physical correlate of consciousness. (Taylor 2002, McFadden 2002, Pockett 2002, Pockett 2000, Stapp 1987, Stapp 1985) Evidence for the electromagnetic hypothesis has been presented particularly by McFadden. However, the very close causal connection between the activation of a dendron and the activation of an electromagnetic field in the neighborhood of that dendron makes it difficult to distinguish between these two proposals empirically.

More germane to our topic is the second component of Eccles' proposal, namely that quantum effects are important in brain dynamics in connection with cerebral exocytosis. This conclusion is plausible, and indeed inescapable. Exocytosis is instigated by an action potential pulse that triggers an influx of calcium ions through ion channels into a nerve terminal. These calcium ions migrate from the ion-channel exits to sites on or near the vesicles, where they trigger the release of the contents of the vesicle into the synaptic cleft. The diameter of the ion channel through which the calcium ion enters the nerve terminal is very small, less than a nanometer, and this creates, in accordance with the Heisenberg uncertainty principle, a correspondingly large uncertainly in the direction of the motion of the ion. That means that the quantum wave packet that describes the location of the ion spreads out, during its travel from ion channel to trigger site, to a size much larger than the trigger site (Stapp 1993/2003). That means that the issue of whether or not the calcium ion (in combination with other calcium ions) produces an exocytosis is a quantum question basically similar to the question of whether or not a quantum particle passes through one or the other slit of a double-slit experiment. According to quantum theory the answer is 'both.' Until the brain process reaches the level of organization corresponding to the occurrence of a Process I action one must in principle retain *all* of the possibilities generated by the Schroedinger equation, Process **2**. In particular, one must retain both the possibility that the ion activates the trigger, and exocytosis occurs, and also the possibility that the ion misses the trigger site, and exocytosis does not occur.

For cortical nerve terminals the observed fraction of action potential pulses that result in exocytosis is considerably less than 100%. This can be modeled classically. (Fogelson 1985) But the large Heisenberg uncertainty in the locations of the triggering calcium ions, entails that the classical uncertainties will carry over to similar quantum uncertainties, and the two possibilities at each synapse, 'exocytosis' and 'no exocytosis', will, prior to the occurrence of the Process **3** action, *both be present* in the quantum state S(t). If N such synaptic events occur in the brain during some interval of time in which no Process **3** events occur, then the state S(t) of the brain will evolve during that interval into a form that contains (at least) 2^N contributions, one for each of the alternative possible combinations of the 'exocytosis' and 'no exocytosis' options at each of the N synapse events.

There is a lot of parallel processing and redundancy in brain dynamics and many of these possible contributions may correspond to exactly the same possible experience 'e'. But in real life situations where there could be several different reasonable actions, one cannot expect that every one of the 2^N alternative possible brain states will be a neural correlate of *exactly* the same possible 'e'. If the agent is conscious then the von Neumann Processes **1** and **3** must enter to determine which of the various alternative possible experiences 'e' actually occurs.

The analysis just given assumes, in accordance with the model of Fogelson and Zucker (Fogelson 1985), that the condition that triggers exocytosis is the presence of a specified number of calcium ions on a trigger site. Beck (2003) considers another possibility. He says that the "low exocytosis probability per excitatory impulse …means that there is an activation barrier against opening an ion channel in the PVG (presynaptic vesicular grid). He proposes that "An incoming nerve pulse excites some electronic configuration to a metastable level, separated energetically by a potential barrier V(q) from the state that leads to the unidirectional process of exocytosis." In this scenario the state in which the exocytosis does occur can be considered to be connected by a *quantum tunneling process* to the state where it does not occur.

Beck's tunneling mechanism would achieve the same result as the mechanism, described above, which is based simply on the spreading of the wave packets of the calcium ions due to Heisenberg's uncertainty principle. Both mechanisms lead to the result that the brain state S(t) will contain 2^N states, defined by the independent 'exocytosis or no exocytosis' option at each of the N synapses. Hence the Eccles-Beck model does not lead to any essential difference, as regards this key point, from the model that emphasizes the spreading of the calcium ions inside the nerve terminal.

The Eccles-Beck proposal does, however, differ significantly from the von Neumann/Stapp proposal in regard to their third point. The vN/S theory attributes the efficacy of will to the assumed power of mental effort to increase the rate of Process **1** actions, whereas the Eccles-Beck proposal attributes the efficacy of will to the assumed power of mental effort to modify *the probabilities associated with the Process **3** action*, the collapse of the quantum state.

The vN/S proposal stays rigorously within the framework of relativistic quantum field theory, and hence produces no causal anomalies, such as the possibility of sending messages backward in time. The Eccles-Beck proposal, by violating the basic quantum probability rules, would in principle allow such anomalies to occur.

It is often emphasized, *correctly*, in connection with quantum approaches to brain dynamics, that "the environment" will be affected differently by interactions with the brain states in which an exocytosis has or has not occurred, and that this difference will destroy, almost immediately, all (practically achievable) interference effects between these macroscopically distinct states.

This *environmental decoherence effect* is automatically included in the formulas used here, which refer explicitly to the brain state S(t), which is the brain-state statistical operator obtained by averaging (tracing) over all non-brain variables.

It is then sometimes concluded, *incorrectly*, that one can immediately replace the brain state S(t) by just *one* of these 2^N components. That conclusion might follow if one were to ignore Process **1**, which is part of the brain process that defines which of our alternative possible thoughts occurs next. Since Process **1** is part of the process that determines which thought occurs next, it should depend upon the state S(t) of the brain *before* the thought occurs, not on the part of that state that will eventually be actualized. Hence all of the 2^N components of S(t) should be retained prior to the Process **3** 'collapse,' whether they interfere or not: Process **3** is, according to the standard rules, the only thing that produces a violation of the Process **2** equation of evolution.

The model of the brain used above, with its 2^N well defined distinct components is, of course, highly idealized. A more realistic model would exhibit the general smearing out of all properties that follows from the quantum smearing out of the positions and velocities of all the particles. Thus the state S(t) prior to the collapse cannot be expected ever to be rigorously divided, solely by Process **2** action, including interaction with the environment, into strictly orthogonal non-interfering components corresponding to distinct experiences. It is Process **1** that makes this crucial separation, not Process **2**. The recognition of the need to bring in a *separate process to define the question* is the critical element of the Copenhagen approach, and it was formalized by von Neumann as Process **1**. Any attempt to ignore Process **1** faces daunting challenges.

Beck, F. & Eccles, J. (2003). Quantum Processes in the Brain: A scientific basis of consciousness. In N. Osaka (Ed.), *Neural Basis of Consciousness*. Amsterdam, Philadelphia: John Benjamins.

Eccles, J.C. (1990). A unitary hypothesis of mind-brain interaction in the cerebral cortex. *Proceedings of the Royal Society of London, B240*, 433-451.

Eccles, J.C. (1994). *How the self controls its brain.* Berlin, Heidelberg, New York: Springer.

Beck, F.,& Eccles, J.C. (1994). Quantum processes in the brain: A scientific basis of consciousness. In Naoyuki Osaka (Ed.), *Neural Basis of Consciousness*. Amsterdam, Philadelphia: John Benjamins.

6. The Jibu-Yasue Approach.

The preceding sections are conservative and incomplete. They are conservative because they: (1), build on the orthodox philosophy of quantum theory, which recognizes that science, like every human endeavor, arises from the fact that human beings choose their actions, and experience the feedbacks; and (2), exploit the quantum laws that relate these choices to those feedback.

The earlier sections are incomplete because they say very little about the actual brain mechanisms.

There is a related question of how memories are stored. Karl Pribram has suggested (Pribram 1966, 1991) that consciousness operates on principles similar to that of a hologram, in which tiny variations of a myriad of physical variables, dispersed over a large region, combine to modulate a carrier wave. These physical variables might be the strengths of the synaptic junctions. Pribram identifies the dendritic network (a dense set of neural fibers) as the likely substrate of such a brain process.

This holographic model would appear to be implementable within quantum electrodynamics, which is the physical theory that is normally be expected to control brain dynamics. However, Umezawa and co-workers (Riccardi, 1967: Stuart 1978, 1979) have suggested that an exotic physical process is involved, namely one similar to what appears in the theory of superconductively. That theory is characterized by the existence of a continuum of states of the same (lowest) energy, and Umezawa suggested that long-term memory is associated with the breaking the symmetry of these ground states, instead of, for example, enduring changes in the physical structures of nerve cells.

Jibu and Yasue (Jibu 1995) have attempted to weave these ideas of Pribram and Umezawa into a unified quantum theory of brain dynamics (QBD). Their theory takes the substrate associated with Umezawa's ideas to be the water that pervades the brain. Excitations of certain states of the water system are called corticons, and they interact with photons in the electromagnetic fields of, for example, the dendritic network. They say:

"With the help of quantum field theory, we have found that the creation and annihilation dynamics of corticons and photons in the QBD system in the sub-microscopic world of the brain to be the entity we call consciousness or mind."

It is not clear why “the creation and annihilation dynamics of corticon and photons” should entail the defining characteristic of conscious process, namely the way that it “feels,” nor what feature of this physically described process *can actually be* a conscious feeling, nor how *definite thoughts* emerge from this essentially quantum process, with its rampant inherent quantum uncertainties. The structure described by QBD must apparently be placed within the general von Neumann framework in order to be tied to human experience. Whether we need the immense theoretical richness of QBD, as contrasted to normal QED (quantum electrodynamics), to accommodate the empirical data of psychology and neuroscience remains to be seen. The projection operators P(e) can introduce the pertinent nonlocal structure. But surplus degrees of freedom bring ambiguities into the structure. Hence the more restrictive QED – which is both well defined and massively validated – would appear to be the more promising candidate.

Pribram, K. H. (1966). Some dimensions of remembering: Steps towards a neurophysiological theory of memory. In J. Gaito (Ed.), *Macromolecules and behavior*, (pp. 165-187) New York, NY: Academic Press.

Pribram, K. H. (1991). *Brain and Perception*. New Jersey: Lawrence Erlbaum.

Riccardi, L.M. & Umezawa, H. (1967). Brain and physics of many-body problems. *Kybernetik* 4, 44-48.

Stuart, C.I.J.M,, Takahashi, Y., & Umezawa, H. (1978). On the stability and nonlocal properties of memory. *Journal of theoretical biology*, 71, 605-618.

Stuart, C.I.J.M,, Takahashi, Y., & Umezawa, H. (1979). Mixed-system brain dynamics: neural memory as a macroscopic ordered state. *Foundations of Physics* 9, 301-327.

Jibu, M. & Yasue, K. (1995). Quantum brain dynamics and consciousness. Amsterdam and Philadelphia: John Benjamins.

7. Directions for Future Research.

Von Neumann's formulation of quantum theory brings human minds directly into brain dynamics via the operators P(e), which specify the neural correlates of a person's conscious experiences. A principal task is now to map out these mind-brain connections, and understand in more detail the principles by which they operate.

These tasks are facilitated in quantum theory, vis a vis classical theory, by the fact that the mapping between the two domains enters explicitly into the dynamical equations in a way that allows conscious efforts to causally influence brain activity in a way generally concordant with William James's theory of ideo-motor action and volition. The explicitly represented causal connection between effortful choosing and experiential feedback allows the functional efficacy of the intentional conscious thought to enter naturally, through trial-and-error learning, into the determination of the mapping P(e): each of us conditions, by practice, his own brain so that his felt intentional efforts will produce the intended experiential feedbacks. The fact that this sort of conditioning works would seem to imply that our conscious efforts do have physical consequences.

A closely connected issue is the Nature of the causal origin of the choices described by Process 1. How do the prior '*states of the brain'* and '*states of consciousness'* influence these choices? Quantum theory opens up the physical theory in a way that accommodates causally efficacious consciousness. And it imposes strong conditions on how it works. But it does not specify the model completely. The general formulas of Newton did not completely specify all of the details of classical physics, and, similarly, the general formulas of von Neumann do not completely specify all of the details of neuropsychological theory.

Throughout this survey I have generally adhered to the pragmatic scientific perspective, rather than the ontological one. The pragmatic view is that science is a human effort involving human thoughts and their useful consequences in the realm of human experiences. It is not an attempt to comprehend the ultimate Nature of reality. Within that restricted scientific framework human thoughts stand out, because the entire conceptual structure is inside human thought and about human thought. Within that framework, dogs, horses, and chimpanzees are treated as parts of the world that always evolve in accordance with the local mechanical Process **2**.

On the other hand, science broadly conceived encompasses evolutionary biology, and that leads to the central question of under what conditions do the Process **1** and the associated Process **3** come into play. The problem here is primarily not that of creating an answer that will be compatible with the available data but rather that of creating data that will distinguish between a plethora of conceivable possibilities compatible with the data about the content of the experiences of non-humans.

The existence of these outstanding issues emphasizes an important fact: the possibility of advancing our scientific understanding of consciousness that is opened up by requiring that understanding to be compatible with the laws of physics has just barely begun. Success of this program will require the efforts of many scientists other than physicists.

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